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CONTRIBUTION TO THE STUDY OF DEEP FOCUS EARTHQUAKES.

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(With 2 figures.)

Zusammenfassung: Wenn das Zeitintervall $S—P$ zwischen dem Eintreffen der direkten Longitudinalwellen und der direkten Transversalwellen genau bekannt ist, ergibt sich aus Laufzeittabellen die entsprechende Laufzeit $P—O$ der Longitudinalwellen unabhängig von der Herdtiefe, falls die POISSONsche Zahl konstant ist, was in der Erde mit genügender Annäherung der Fall ist. Lediglich die Herddistanz, die in Tabellen für normale Herdtiefe angegeben ist, bedarf einer Korrektur, die in Fig. 2 für verschiedene Herdtiefen unter Benutzung der von SCRASE (1) berechneten Laufzeiten sowie der Laufzeittabellen von JEFFREYS (3) gezeichnet ist, und zwar getrennt a) für $S—P$ und b) für $P—O$. Bei den Laufzeiten von JEFFREYS für P ist dabei die additive Konstante zu 6 Sekunden angenommen worden, und diese Zahl wurde zu allen Tabellenwerten für P addiert. Die Herdtiefe kann am besten aus den Laufzeitdifferenzen $pP—P$ und $sP—P$ gefunden werden, die nur wenig von der Herdentfernung abhängen (vgl. Tab. 3), dagegen stark von der Herdtiefe (Fig. 1).

Schließlich können die in der vorstehenden Arbeit diskutierten Phasen $P'P'$ usw. zur Bestimmung der Herddistanz und Herdtiefe benutzt werden. Insbesondere hängt $P'P'—P$ praktisch nicht von der Herdtiefe ab, so daß diese Zeitdifferenz zur Bestimmung der Herddistanz ohne Rücksicht auf die Herdtiefe benutzt werden kann (Fig. 3 der vorangehenden Arbeit), während $P'P'—O$ dann zur Ermittelung der Herdtiefe dient. Ähnliches gilt für $P'P'P'$. $ScPcPP'$ kann zur Kontrolle benutzt werden.

Tab. 2 zeigt die gute Übereinstimmung der mit Hilfe von JEFFREYS Tabellen für normale Herdtiefe aus $S—P$ ermittelten Herdzeit für ein Beben mit einer Herdtiefe von etwa 350 km unter Benutzung verschiedener Stationen, während in Abschnitt V ein Beispiel für die Bearbeitung eines Bebens mit tiefem Herd auf Grund der Angaben einer Station angegeben ist. Im Schlußabschnitt werden einige Angaben über die in Pasadena registrierten Beben mit anormal tiefen Herden gemacht.

I. Introduction.

In the following pages are presented certain rapid and convenient methods for interpreting the records of deep-focus earthquakes. These

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methods are in regular use at Pasadena, and furnish the basis for the discussion of new phases in the preceding paper. The procedure is by no means in a final state; it is offered here in justification of the preceding results, and as a contribution to the rapidly developing theory of these interesting shocks.

II. Determination of origin time.

In investigating normal shocks, having at hand the readings from a number of stations, the usual preliminary procedure is to determine from *S—P*, or from some other phase interval, the epicentral distance of each station. In each instance the usual tabulations simultaneously yield values of the time of origin. If these times, as determined from the data of different stations, are in reasonable agreement, it is presumed that the distances are correct; a preliminary epicentre is then determined by some graphical method, and an origin time settled upon by some process of averaging. This method was followed for the normal shocks discussed in the preceding paper; it obviously requires modification in case of deep focus.

Fortunately, the method is applicable to the determination of origin time, even for very deep earthquakes, provided that the interval *S—P* is correctly identified. The agreement of origin times from different stations is surprisingly good, in spite of the fact that the distances read from the usual tables are then considerably in error.

This rather unexpected result is due to the circumstance that Poisson's ratio is nearly constant in the mantle of the earth. The consequence is a nearly constant ratio of the travel times of *S* and *P* at all distances. Since, even for normal shocks, the paths of *S* and *P* to stations at the larger distances penetrate nearly to the core, it is clear that this constant ratio will apply to waves from deep shocks.

The following table (Table 1) is calculated from the travel-times given by Jeffreys (3). The additive constant term in the travel time of *P* is taken as 6 seconds, and Jeffreys' values of t_p are accordingly increased by 6 seconds to give the tabulated *P—O*.

Considering how small the change in the ratio $(P—O)/(S—P)$ is in passing from the comparatively shallow paths for distance 10° to the very deeply penetrating ones for 100°, it is obvious that the change in $(P—O)/(S—P)$, consequent on increasing the depth of the hypocenter from near the surface to even the relatively great depth of 0.10 (637 km.), must be quite small.

Table 1.

Distance (degrees)	$S—P$ (seconds)	$P—O$ (seconds)	$(P—O)/(S—P)$
10	112	147	1.31
20	217	275	1.27
30	302	377	1.25
40	367	462	1.26
50	430	540	1.26
60	492	612	1.24
70	549	676	1.23
80	604	734	1.22
90	653	785	1.20
100	696	833	1.20

This is confirmed by such results as those given in Table 2. The data are those of a moderately deep shock (h of the order of 350 km.). All except those for Pasadena and Tinemaha are taken from station reports, and are thus subject to errors of reading, interpretation, etc. The values of $P—O$ are 6 seconds greater than the t_p corresponding to the given $S—P$ in JEFFREYS' tables. The calculated origin times agree very well—quite as well as is usual with similar data for normal shocks. No effect of distance is apparent, as the data of stations at widely differing distances yield origin times which differ no more than those for stations at nearly the same distance. It is noteworthy that the first few stations of Table 2 are at distances such that the travel-times should be nearly the same for a shock at this depth as for a normal shock.

From these results it appears that the origin time can be determined from the times of S and P at a single station, making use of the tabulated travel-times for normal shocks, regardless of the depth of focus, with an error which is no greater for deep shocks than for normal ones.

III. Determination of depth (from *pP* and *sP*).

No deep focus shocks are known to have occurred within 45° of the Pasadena station; very few are clearly recorded from beyond 90°, the majority being between 60° and 90°. Accordingly, our attention has been directed to convenient determination of depth for shocks in the range of distance last mentioned.

At these distances, pP and sP are usually well recorded and easily identified. From published seismograms it appears that this may also

Table 2.
Earthquake of September 23, 1932. $h/r_0 = 0.05—0.06$.

Station	P observed at 14^h +	$S—P$ observed	$P—O$ from table	O calcul. 14^h +
	m s	m s	m s	m s
Tyôsi	24 18	1 39	2 11	22 07
Numazu	24 29	1 42	2 15	22 14
Osaka	24 35	1 56	2 31	22 04
Hukuoka	25 04	2 20	3 02	22 06
Nagasaki.	25 13	2 34	3 20	21 53
Chiufeng	25 50	3 08	4 00	21 50
Zikawei	26 12	3 21	4 16	21 56
Nanking	26 18	3 26	4 22	21 56
Irkutsk	27 00	3 51	4 51	22 09
Hongkong	27 55	4 35	5 43	22 12
Manila	28 27	5 07	6 23	22 04
Phu-Lien	28 42	5 11	6 28	22 14
Sverdlovsk	30 25	6 38	8 21	22 04
Sitka	30 59	7 00	8 48	22 11
Honolulu	31 32	7 31	9 24	22 08
Batavia	31 33	7 41	9 36	21 57
Kučino	31 47	7 37	9 31	22 16
København	32 53	8 46	10 48	22 05
Bozeman.	33 01	8 51	10 55	22 06
Hamburg	33 07	9 02	11 07	22 00
Potsdam	33 09	8 54	10 57	22 12
Tinemaha	33 14	9 08	11 13	22 01
Wien	33 17	9 15	11 21	21 56
Jena	33 19	9 03	11 08	22 11
Beograd	33 22	9 00	11 04	22 18
Pasadena	33 24	9 14	11 21	22 03
De Bilt	33 27	9 13	11 19	22 08
Stuttgart	33 33	9 23	11 30	22 03
Stonyhurst.	33 33	9 16	11 23	22 10
Uccle	33 34	9 19	11 26	22 08
Strasbourg	33 37	9 21	11 28	22 09
Innsbruck	33 38	9 24	11 32	22 06
Kew.	33 39	9 27	11 35	22 04
Zürich	33 40	9 26	11 34	22 06
Chur	33 43	9 28	11 36	22 07
Paris	33 47	9 33	11 42	22 05
Neuchâtel	33 48	9 26	11 34	22 14
Helwan	33 55	9 35	11 44	22 11
Tucson	33 56	9 52	12 01	21 55
St. Louis.	34 21	10 00	12 10	22 11
Cartuja	34 46	10 30	12 40	22 06

apply to greater and smaller distances. Now, the intervals *pP—P* and *sP—P* are nearly independent of distance, but vary considerably with depth, as may be seen from the following table (Table 3).

Table 3.

	pP—P (sec.)			*sP—P* (sec.)		
Depth	0.03	0.06	0.09	0.03	0.06	0.09
$\Delta = 30°$	39	70	—	61	116	160
$\Delta = 50°$	43	80	113	63	120	173
$\Delta = 70°$	44	84	118	62	121	174
$\Delta = 76°$	45	84	120	64	122	176
$\Delta = 90°$	46	86	121	65	126	179
$\Delta = 180°$	46	92	136	66	132	195

The values for 76° and for 180° (which latter refer to *pP'—P'* and *sP'—P'*) have been calculated by Scrase (1). The others were found by interpolation from the travel-times given by the same author. For depth 0.09, *pP* exists only at distances over 36°.

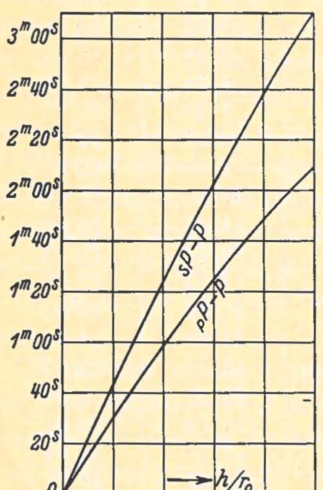

Fig. 1.
sP—P and *pP—P* as functions of depth of focus, calculated for distances of 50° to 100°.

In Fig. 1 average values of *pP—P* and *sP—P* are plotted against depth of focus. When these phases have been identified, reference to this chart affords a ready means of determining the depth of focus.

This method is that used in determining the depth for the shocks discussed in the preceding paper. From the results of that investigation it appears that the new phases *P'P'*, etc. can be used for the same purpose. Details will be found in the final section of the present paper.

IV. Determination of distance.

The distance of a deep shock is equal to that of a normal shock with the same *S—P* or *P—O*, plus a correction which, when the depth is known, can be found from the tabulations of Scrase (1). These corrections are given in Figures 2a and 2b. The correction is to be added to the distance of the corresponding normal shock, as found from Jeffreys' tables. (*P—O* is 6 seconds greater than Jeffreys' t_p.)

The difference between the two groups of corrections is due to the facts that POISSON's ratio is not constant, and that the travel-times used in calculation are not exact (especially for S).

In cases where there is some doubt as to the identification of S, and in all cases as an additional verification, the arrival times of other

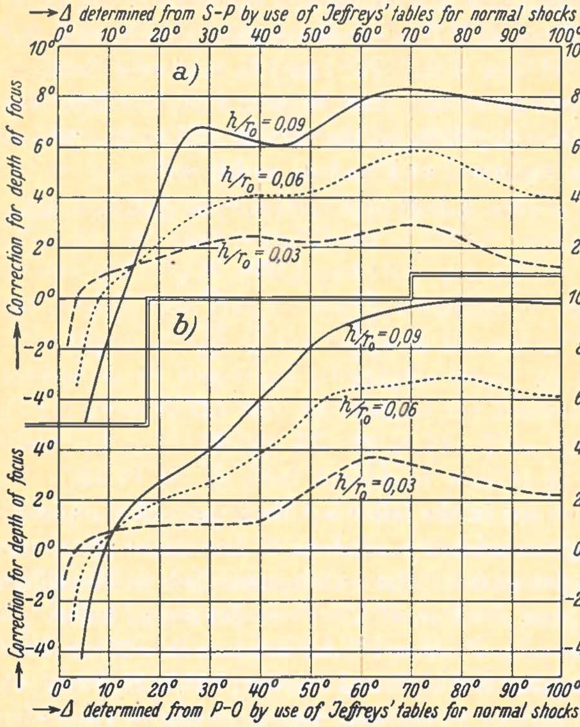

Fig. 2. Corrections for depth of focus to be added to distances found from JEFFREYS' tables: (a) from S—P; (b) from P—O.

marked phases can be compared with the travel-times given by SCRASE and others, in order to arrive at a precise value of the distance.

V. Determination of distance and depth by means of $P'P'$ etc.

In the course of the investigations detailed in the preceding paper it became evident that, besides their theoretical interest, the new phases $P'P'$, etc. promise to be of considerable practical value in the study of deep earthquakes. Naturally, these properties could not be used in finding distances and depths for the earthquakes employed to establish the phases in question; but for future shocks this is of course quite possible.

As pointed out in the preceding paper, $P'P'$—P and $P'P'P'$—P are nearly independent of depth. They can thus be used to determine distance without reference to depth. (Cf. Figs. 3, 5b of the preceding paper.) If the origin time is known, say from S—P, then the travel time of $P'P'$ or $P'P'P'$ gives the depth. The interval $ScPcPP'$—P, and the travel-time of $ScPcPP'$, may be used as a check.

The whole procedure may be seen from the following example.

After the completion of the manuscript for the preceding paper, a shock was registered at Pasadena as follows:

1933 Oct. 25	*i P*	23^h	39^m	38^s	dilatation, from southeast
	i 2			57	
	e 3		40	14	
	i 4			35	
	e 5		41	04	
	i 6		49	03	
	i 7			31	
	e 8		50	44	
	e 9	24	06	52	
	i 10		10	13	

For reference in the following discussion, all the phases except P have been given arbitrary numbers. A few minor phases are omitted.

The appearance of the seismograms led to identification of *i* 6 as S. This gives S—P = $9^m\ 25^s$. From Jeffreys' tables $t_p = 11^m\ 26^s$; adding 6 seconds, P—O = $11^m\ 32^s$, whence O = 23:28:06. The corresponding distance for a normal shock is 72°.7. However, the absence of recorded surface waves, and the occurence of clear phases in the first two minutes, plainly indicate deep focus, so that the distance must be corrected for depth.

The phases *i*2 and *i*7 being tentatively identified as PcP and ScS, a rough check on the origin time is possible. Because of the approximate constancy of Poisson's ratio, if we take ScS—PcP = $9^m\ 34^s$, and find from the same tables the value of P—O corresponding to an equal value of S—P, this result should be approximately PcP—O. For S—P = $9^m\ 34^s$ we find P—O = $11^m\ 36^s + 6^s = 11^m\ 42^s$; since PcP = *i*2 = 23:39:57, we have O = 23:28:15. The agreement is sufficiently good to verify the identification of PcP and ScS. (When available, SS—PP, and similar intervals of corresponding phases can be used in the same way, to find PP—O etc.)

To find the depth of focus it is desirable to identify pP and sP. There are two possibilities; either $e3$ is pP and $i4$ is sP, or $i4$ is pP and $e5$ is sP. In the first case $pP—P = 36^s$ and $sP—P = 57^s$; and from Fig. 1, $h = 0.025 \pm$. In the second case $pP—P = 57^s$ and $sP—P = 86^s$; whence $h = 0.04$.

From Fig. 2a we now find the correction to be applied to Δ; on the first hypothesis this is $+ 2°$, on the second it is $+ 4°$. The corresponding distances hence are $75°$ and $77°$.

With the results so far obtained there can be no doubt that $e9$ is $P'P'$ and $i10$ is $ScPcPP'$. We have then $P'P'—P = 27^m\ 14^s$, and from Fig. 3 of the preceding paper, Δ must be close to $76°$. As $P'P'—O = 38^m\ 46^s$, Fig. 2 of the same paper shows that $h = 0.04$. The values $ScPcPP'—P = 30^m\ 35^s$ and $ScPcPP'—O = 42^m\ 07^s$ agree well with these conclusions. (Cf. Fig. 4 of the preceding paper.)

The final result is thus that the source is distant $76°$ southeast of Pasadena, at a depth of 0.04 of the radius of the earth. These data were incorporated in an immediate telegraphic report on this shock.

Through the press at the time we received the following readings from Fordham: $P = 23:38:31$, $S = 23:46:53$. This gives $P—O = 10^m\ 21^s$, $O = 23:28:10$, in good agreement with O as calculated from the Pasadena readings. With $h = 0.04$, we find $\Delta = 65°$. Combining this with the distance of $76°$ found for Pasadena, the indicated epicenter is just within the border of Argentina, 100 to 200 km. northwest of Salta. A later press report from Buenos Aires gave a distance of approximately 1000 miles (1600 km. approx.) northwesterly from Buenos Aires, based on seismographic data. This is in good agreement. No further data are available at this writing.

VI. Concluding remarks.

Thus far, we have identified on the Pasadena records only three very clear cases of deep focus shocks in South America; and of these two are extremely recent. All three epicenters lie some hundred kilometers inland: that of July 18, 1931, in southwestern Bolivia; that of August 29, 1933, in northwestern Brazil or northern Bolivia; and that of October 25, 1933, in northwestern Argentina, as just shown. This is in contrast with the South American shocks at normal depth, which usually occur near or off the coast; a circumstance already noticed by TURNER.

A similar remark applies to many of the remaining deep focus shocks recorded at Pasadena. These have occured chiefly in a belt extending from Manchuria across Japan, thence by way of the Bonin Is., Marianne Is., and Solomon Is. to the Fiji and Kermadec regions; and especially the deeper of them occur further from the center of the Pacific than the normal shocks of the same general region.

Some of the methods presented in this paper are applicable to the study of shocks recorded even in the first years of precise seismology. An excellent instance is the large shock of January 21, 1906. It was pointed out by ZOEPPRITZ in 1908 that the surface waves were recorded with only about $^1/_{100}$ of the amplitude to be expected for a normal shock with the same amplitude in the preliminaries. This shock has been investigated several times with different results; as WADATI (2) has pointed out, the discrepancies are due to not considering possible large depth of focus. Reexamination of the scanty data now indicates an epicenter not far from Tokio, with a depth about 0.06.

Notes added in proof.

Since the completion of this paper, a number of additional cases of deep-focus shocks have been found, in which the phases *P'P'*, etc., could be identified. One such case is the shock of 1933 Jan. 1, at 9^h, which had been supposed to be normal, but now appears to have had a depth of about 0.03. Another is that of 1933 Oct. 12, at 7^h, with a depth about 0.02, off the coast of Chile, near 43° S. Lat. A number of cases of deep-focus shocks in that locality are to be found in the International Seismological Summary [see V. CONRAD, this journal **40** (1933), 121]. The remarks as to the inland occurrence of deep-focus shocks in South America should be modified accordingly.

Further data now in hand for the shock of 1933 Oct. 25, at 23^h, serve to confirm the conclusions as to depth, origin time, and location, within the limits of reasonable error.

An important paper by K. WADATI and K. MASUDA [Geophys. Mag. Tokyo **7** (1933) 269] has just become available. Their data on travel-times for deep-focus earthquakes lead to values for *sP—P*, for *pP—P*, and for the corrections to distance, which differ only slightly from those given in Figs. 1 and 2 above, except for distances over 75° (Fig. 2). The discrepancies at the larger distances are due to fact that these authors assume $(S—O)/(P—O) = 1.794$ for all distances and depths; whereas, according to JEFFREYS, along the deeper paths, as observed at the larger distances, *S* arrives about 8 seconds later than as given by this hypothesis. Consequently, the corrections to distance calculated from the data of WADATI and MASUDA are greater than those given in Fig. 2 the deviations increasing with depth and distance to 3° at distance 100° and depth 500 km., the largest values given by these authors.

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